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Some Lessons from Yogyakarta Earthquake of May 27, 2006

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ABSTRACT

The earthquake of moment magnitude, M_w 6.3 in Yogyakarta and Central Java on May 27, 2006 caused widespread death and destruction to the heavily populated and relatively prosperous region. More 5,800 people were killed and robbed hundreds of thousands of residential buildings, and hundreds other structures were also destroyed. This paper presents some observations of the earthquake effects in geological and geotechnical aspects. Yogyakarta region has located on a soft sediment deposit. Therefore, low frequency contents of the seismic wave may have been amplified. The vertical and horizontal PGA at a seismograph station YOGI was 0.183 to 0.303 g and 0.197 to 0.336 g respectively. Based on the high ground peak acceleration on soft soil, several severity levels of observed infrastructure damages were geotechnical related. From field observations, it was found that the geotechnical effects included major landslides, liquefactions and fluctuations in the water levels and quality of wells. Local liquefactions were found in several sites in which the water table was relatively shallow. Ground settlements and horizontal displacement were also observed in several locations where several signs of liquefaction were found nearby. The region affected lies on debris of a subduction zone, hence amplification of horizontal shaking, as observed by the high amplification ratios have played a significant role in the widespread destruction observed.

INTRODUCTION

On May 27, 2006, a magnitude 6.3 earthquake on the moment magnitude scale and lasted for 52 seconds struck Central Java and Yogyakarta, center for Javanese traditional arts and culture as well as a center of Indonesian higher education. Because the earthquake was relatively shallow under ground, shaking on the surface was more intense than deeper earthquakes of the same magnitude, resulting in major devastation, in particular in the districts of Bantul in Yogyakarta Province and Klaten in Central Java Province. The earthquake took over 5,700 lives, injured around 38,000 more and robbed hundreds of thousands of residential buildings. Meanwhile, the Mt. Merapi's volcanic activity was increasing and producing lava flows, toxic gases, and clouds of ash, prompting the evacuation of tens of thousands of people. At the same time, the government of Indonesia started the emergency response procedures right after the earthquake while preparing reconstruction and recovery programs. The earthquake was the third major disaster to hit Indonesia within the past 18 months. In December 2004, a major earthquake followed by a tsunami devastated large parts of Aceh and the island of Nias in North Sumatra, and in March 2005, another major earthquake hit the island of Nias again. With Indonesia's more than 18,000 islands along the Pacific "ring of fire" of active volcanoes and tectonic faults, the recent disaster is a reminder of the natural perils facing this country.

A comprehensive analysis by a team of Indonesian Government and international experts estimate the total amount of damage and losses caused by the earthquake at Rp 29.1 trillion, or US$ 3.1 billion. Total damage and losses are significantly higher than those caused by the tsunami in Sri Lanka, India and Thailand and are similar in scale to the earthquakes in Gujarat on 2001 and in Pakistan on 2005 (BAPPENAS 2006). The damage was very heavily concentrated on housing and private sector buildings. Private homes were the hardest hit, accounting for more than half of the total damage and losses (15.3 trillion IDR). Private sector buildings and productive assets also suffered heavy damage (estimated at 9 trillion IDR) and are expected to lose significant future revenues. An estimated 154,000 houses were completely destroyed and 260,000 houses suffered some damage. More houses will have to be replaced and repaired than in Aceh and Nias at a total cost of about 15% higher than the damage and loss estimate of the tsunami. The impact of the earthquake on public and private infrastructure was relatively limited, with the value of damage and losses estimated at 397 billion IDR and 153.8 billion IDR, respectively. The sector worst affected is energy with damage to the electricity transmission and distribution facilities estimated at a total Rp 225 billion and losses at a further 150 billion IDR from physical damage.

The aim of this paper is to gain some lessons learned from Yogyakarta's earthquake on 27 May 2006, particularly in geotechnical aspects and collapsed structures. In the case of liquefaction, geo-electrical surveys were carried out in selected area in order to investigate the underground faults below the liquefaction sites. Some illustrations of seismological condition and observed faults are also presented.

SEISMOLOGICAL CONDITION

Understanding the Yogyakarta earthquake in a regional setting, and hence understanding its implications on earthquake hazard, requires understanding the larger region extending to the north, to Andaman and Nicobar Islands, and to the south and east, to the northern tip of Australia and Timor. The global tectonic picture is that of subduction of the Indo-Australian plate under the Eurasian plate along an arc of about 6000 km and at an average rate of about 5 cm/yr. Slip rates on the northern section of the subduction mechanism reach about 7 cm/yr. The location of the earthquake according to the United States Geological Survey (USGS) is 20 km SSE of Yogyakarta City at 7.962^{o}S – 110.458^{o}E.

From BMG (Badan Meteorologi dan Geofisika Indonesia), it is indicated that Yogyakarta City is located on a soft sediment site. Therefore, low frequency contents of seismic wave may be amplified. The subsurface is underlain by young volcanic deposits from Mt. Merapi up to 200 m in thickness. These deposits consist of undifferentiated tuff, ash, breccia, agglomerates and lava flows. Their weathering products, mainly from the lower slopes and the plain extending to the south, are largely alluvial deposits of volcanic debris reworked by small streams from initial deposits on upper slopes. Preliminary information from a few soil borings in Yogyakarta indicates the subsurface consists of 1 0-5 m of loose to medium-dense volcanic fine sand underlain by over 10 to 20 m of dense to very dense sand and silty sand. The groundwater was found approximately 4 to 5 m below the surface (EERI 2006). It can be summarized that the most pronounced effects of the earthquake are associated with directivity and soil amplification. Fig. 1 shows the heavily damaged zones concentrated in two distinct areas: one near the epicenter (Imogiri, Bantul, Plered, Yogyakarta), and other further northeast (Gantiwarno, Central Java). It appears that directivity and proximity to the fault rupture zone, topography, local site conditions, and the vulnerability of older unreinforced masonry homes affected the severity of the damage. Velocity data from 27 stations were provided by BMG. However, for most of the stations, the distance from the epicenter is over 500 km and most of the data is defective due to instrument malfunction. Therefore, only two stations which are at less than 100 km from the epicenter and have relatively useable waveforms are selected for analysis. Distances from the epicenter to the selected stations, YOGI and BJI, are about 10 km and 90 km, respectively. The corrected vertical velocity plots at the YOGI station with velocity data at the BJI station are shown in Fig.2 (Elnashai et al. 2006).

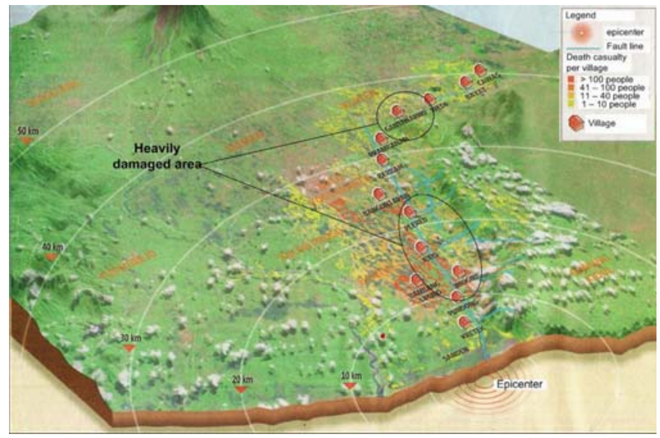


Fig.1.Reported Opak fault and damage to nearby villages (Kompas 2006)

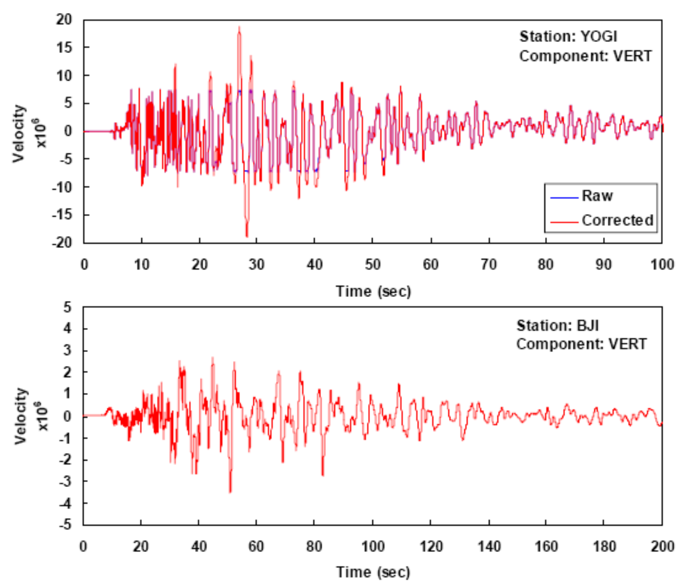


Fig. 2.Vertical velocity data at station YOGI and BJI (Elnashai et al. 2006)

From Elnashai *et al.* (2006) study, they estimated vertical PGA at YOGI station is 0.183g to 0.303g and the horizontal PGA is 0.197g to 0.336g. The PGA at BJI station is evaluated as 0.021 to 0.035g and 0.015 to 0.025g for horizontal and vertical components, respectively. These provide the best available estimates in the absence of more reliable data. For the vertical acceleration spectra reported by Elnashai *et al.* (2006), the highest amplification factor is about 3.0, associated with a relatively broad period range of high amplification. This value is identical with the amplification factor given by Eurocode 8 (EC8) which is based on the proposed spectra by Elnashai and Papazoglou (1997). However, the range of high amplification is 0.05 to 0.15 sec in EC8, while high amplifications in the YOGI record go up to 0.35 seconds. Therefore, this is an unusual feature that may explain the extensive damages and failure of roofs and vertical members in Yogyakarta region.

FAULT-DISPLACEMENT INDUCED DAMAGE

About 50 km from center of Yogyakarta to southern part, it has been found two main faults. The first fault extends to north-east while the second fault stretches to south-west (Rahardjo *et al.* 1977). The first fault expands along the Opak River which is called as Opak fault. The length of fault is about 36 km with zone width is estimated from 200 to 500 m. These faults is not classified as the active fault, however it can be triggered by huge earthquake such as Yogyakarta earthquake occurred on 27 May 2006. Some studies conducted by Sudarno (1997) indicate that the main fault has located under ground along the Opak River. This fault formation was predicted occurs in the Oligo-Miosen tectonics phase (about 25 millions years ago) while south west fault occurred in Pliosen phase was calculated about 1.5 millions years ago (Pramumijoyo *et al.* 2004). This phenomenon caused the uplift of south areas of Wonosari to the height of 200 m from sea water level. From Fig.3, the Opak fault and its damage to nearby areas are presented. The estimated epicenter by NIED (Nakano *et al.* 2006) is located near Opak fault. The epicenter and presumed fault region is well correlated with damage levels in the affected area provided by UNOSAT as shown in Fig.3.

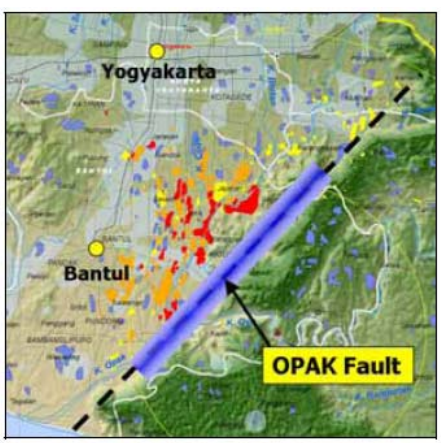


Fig. 3. Opak fault and its near damage areas (http://www.unosat.org)

However, other study from Setiadji et al (2007) based on microseismic surveys on aftershocks which were conducted in the period of June to August 2006 in Yogyakarta, mentioned that the currently seismically active region is not located along the Opak fault. Rather, the observation found that the ruptured fault during the 27 May 2006 earthquake was located about 10 km east of Opak fault, within the domain of Tertiary volcanic edifices. Their conclusion stated that the earthquake 27 May 2006 caused reactivation of an older Tertiary fault. As the location of suspected active fault was remote from the most severely damage areas, they considered that other geotechnical aspects have took dominant control on determining the scales of damage. These included the thickness and types of Quaternary deposits that cover the low-land areas, and engineering aspects of public and private constructions.

LESSONS LEARNED FROM GEOTECHNICAL FEATURES

Landslides and liquefactions were a most dominant ground failure observed. However, site response is postulated to have been one of the most influential parameters in precipitating the extensive damage observed. As mentioned before, the Yogyakarta region affected lies on debris from the subduction mechanism, herein amplification of horizontal shaking, as observed in the high amplification ratios have a significant role in the widespread destruction observed. Other geotechnical effects that were found as hazard are slight ground surface cracks, permanent displacement and fluctuations in the water levels.

Fig.4. Ground slumping at Nglepen - Sengir (Sumberharjo), north of Opak fault (Photograph by Elnashai et al. 2006)

In several areas building foundations were severely affected by ground deformation caused by the landslide reported by Elnashai *et al.* (2006). Figure 4 shows a combination of ground slumping and landslide on the hillside at north of the Opak fault. Housing units built on the hillside were heavily damaged or totally collapsed due to ground failure. Figure 5 shows large ground cracks running through the village. In some pavement roads closed to earthquake epicenter was heaved and damaged, as shown in Fig. 6, along a path in

Bantul. Those cracks are parallel with distance 5 to 10 m apart, and the crack widths are about 4 to 15 cm.

Liquefaction

Liquefaction is a phenomenon in which the stiffness of soil is reduced during earthquake shaking or other rapid loadings. Liquefaction occurs in saturated soils that are soil in which the space between individual particles is completely filled with water. This water exerts a pressure on the soil particles that affects how tightly the particles the particles themselves are pressed together (Chiou and Chen 2007). Prior to an earthquake, the water pressure is relatively low. However, the earthquake can cause the water pressure to increase to the point where the soil particles can move with respect to each other. When liquefaction occurs, the strength of the soil decreases and the ability of a soil deposit to support foundations of buildings and structures are reduced.

Fig.5. Ground cracks near residential area (Photograph by Elnashai et al. 2006)

Fig.6. Ground cracking and settlement due to permanent deformation along a road shoulder

The liquefaction triggered by Yogyakarta earthquake occurred in some locations in region. Liquefied sediments being ejected through ground fissures during the earthquake were also found in certain locations. However, its effects were minimal. Ground settlements and horizontal displacements around the Muhammadiyah University of Yogyakarta (UMY) campus buildings were observed as shown in Fig. 7 and 8. Furthermore, several signs of soil liquefaction were observed nearby (Fig.9).

Fault Investigation in Liquefaction Sites

In order to observe the liquefaction locations along under ground faults (Fig.10), some soil investigation such as geo-electric sounding (resistivity sounding). The equipment used in measurement was resistivity-meter of Oyo McOhm 2115 and the measurement employed the Wenner configuration. In this configuration, the distance between each current and potential electrode must be to be equal (Fig. 11).

Fig.7 Inclined campus floor due to liquefaction

Fig. 8. Horizontal displacement found in Gamping near UMY campus

The measurements were conducted on 10 sites which were named as R-01 to R-10. The raw data from measurement was then calculated using PROGRES. Consequently, the forward modeling and inverse modeling was employed in order to calculate the correct value of true resistivity with minimum error. An example of the resistivity result from the analysis in R-01 is shown in Fig.12. This resistivity value shows the resistivity in each subsurface rock layer under the center point of geo-electric measurement. The resistivity value of rock layer is uncertainty which the value must consider on geological condition.

Fig.9. Liquefaction-induced lateral spreading near the UMY campus buildings

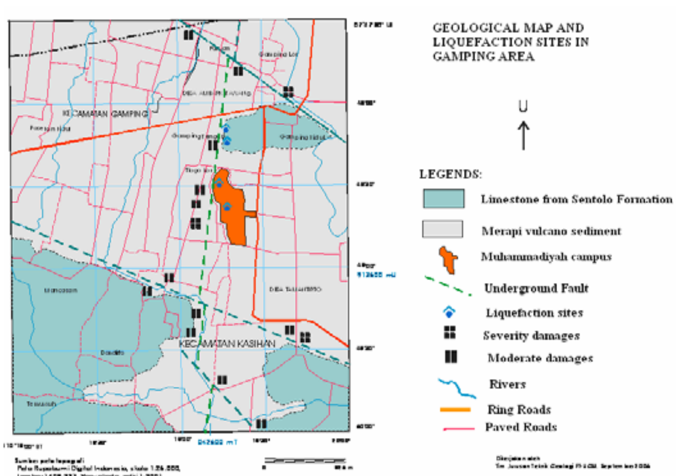


Fig.10. Location of observed liquefaction and underground fault line

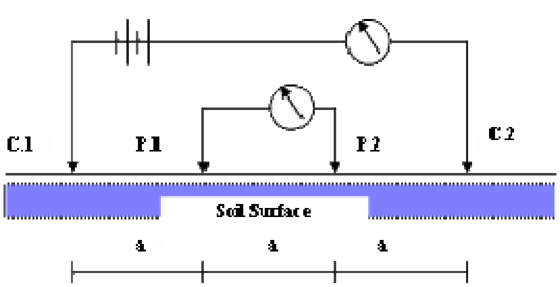


Fig.11 Wenner configuration used in measurement

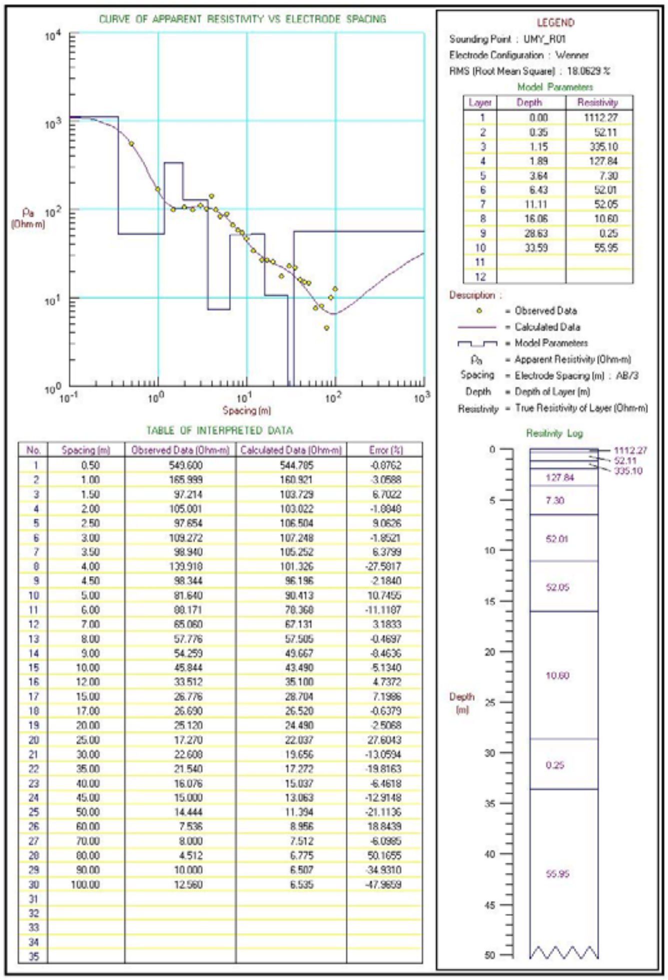
From the measurement, it was found that the resistivity value is varied. The conversion and correlation analysis between these values and geological condition can figure out correct values of the site. Based on bore-log that conducted in selected locations crossing to the geo-electric line, the subsurface rock can be classified as:

1. Subsurface soil to the depth of 2 meter has various resistivity to 1000 ohm-meter, particularly in very dry soil.
2. Clay layers has resistivity value of 0.45 to 4.0 ohm-meter
3. Igneous rock has resistivity values in ranging of 193 to 744 ohm-meter.
4. Sand with gravel from fine to coarse grain has various resistivity value from 7.0 to 26 ohm-meter
5. Massive sandstone has resistivity values of 20 to 78 ohm-meter.
6. Sandstone with gravels has resistivity value of 42 to 100 ohm-meter.

Therefore, contour maps of resisitivity were developed for assisting the subsurface interpretation for the depth of 10, 20, 30, 40, 50 and 80 m. The map represents the lateral distribution of rock resistivity in related depths. Figure 13 shows some examples of contour map used in this study. The final result of observation is presented in Fig.14. The underground fault is clearly detected under liquefaction sites. During earthquake shaking, the water pressure to increase to the point where the soil particles can move with respect to each other. It was also found that the loose to dense sand layer is in depth from 60 to 90 meter over clay layer.

LESSONS LEARNED FROM COLLAPSED HOUSING AND RC STRUCTURES

The most severely affected areas were Bantul in the Province of Yogyakarta and Klaten in Central Java. According to an early report (BAPPENAS 2006), a total 5,716 people died while 37,927 people were injured. Of the total death toll, 4,121 occurred in Bantul, while 1,041 died in Klaten district. A total of 156,664 housing units were totally destroyed. The high level of damage is mainly due to the high density of the population (1600 persons/sq.km) and the almost complete lack of seismic design provisions. The typical house in the affected rural areas is a one-story unreinforced clay brick/block masonry in cement or lime mortar (Fig. 15). The main load-carrying components are unreinforced clay brick masonry walls on which a timber roof system is supported. The gravity loads including slate, metal asbestos-cement or plastic corrugated tiles on roof system. The loads are transferred to rubble stone strip or isolated footing through concrete or wood ring beams. There is no special connection system between timber roof system and the masonry walls. During the past 30 years, reinforced concrete framing systems with half brick masonry infill walls have been used both in rural and urban areas.



Layer	Depth	Resistivity
1	0.00	1112.27
2	0.35	52.11
3	1.15	335.10
4	1.89	127.84
5	3.64	7.30
6	6.43	52.01
7	11.11	52.05
8	16.06	10.60
9	28.63	0.25
10	33.59	55.95
11		
12		

No.	Spacing (m)	Observed Data (Ohm-m)	Calculated Data (Ohm-m)	Error (%)
1	0.50	549.600	544.705	-0.8762
2	1.00	165.999	160.921	-3.0588
3	1.50	97.214	103.729	6.7022
4	2.00	105.001	103.022	-1.8848
5	2.50	97.654	106.504	9.0626
6	3.00	109.272	107.248	-1.8521
7	3.50	98.940	105.252	6.3799
8	4.00	139.918	101.326	-27.5817
9	4.50	98.344	96.196	-2.1840
10	5.00	81.640	90.413	10.7455
11	6.00	88.171	78.368	-11.1187
12	7.00	65.060	67.131	3.1833
13	8.00	57.776	57.505	-0.4697
14	9.00	54.259	49.667	-8.4636
15	10.00	45.844	43.490	-5.1340
16	12.00	33.512	35.100	4.7372
17	15.00	26.776	28.704	7.1986
18	17.00	26.690	26.520	-0.6379
19	20.00	25.120	24.490	-2.5068
20	25.00	17.270	22.037	27.6043
21	30.00	22.608	19.656	-13.0594
22	35.00	21.540	17.272	-19.8163
23	40.00	16.076	15.037	-6.4618
24	45.00	15.000	13.063	-12.9148
25	50.00	14.444	11.394	-21.1136
26	60.00	7.536	8.956	18.8439
27	70.00	8.000	7.512	-6.0985
28	80.00	4.512	6.775	50.1655
29	90.00	10.000	6.507	-34.9310
30	100.00	12.560	6.535	-47.9659
31				
32				
33				
34				
35				

Fig.12. Result of apparent resistivity curve and its data interpretation

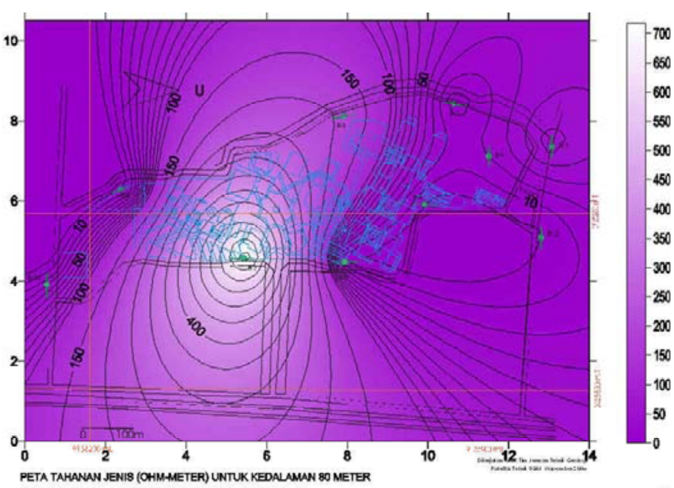


Fig.13. Resistivity contour map for the depth of 80 meter

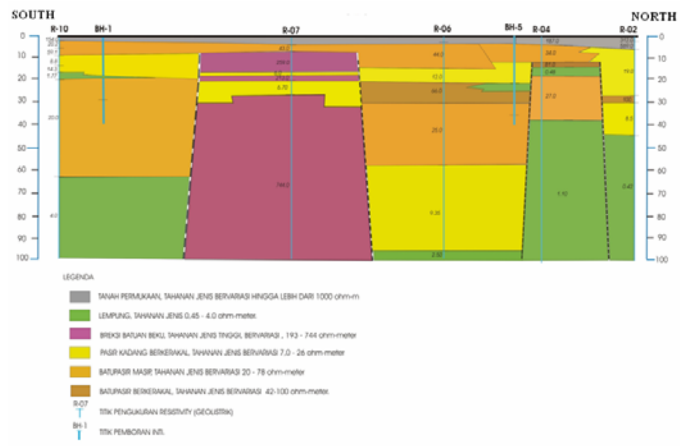


Fig.14 Geological section from geo-electric survey and result from the bore-log observations

Fig.15. Collapsed housing

Fig.16. Collapsed reinforced concrete structures of BPKP building

The main causes of damage to this type of housing are discontinuity of load path and brittle characteristics of materials. Due to poor anchoring of roof-to-wall and wall-to-foundation, there are no continuous load paths to transfer the inertia force from the building to the foundation. In many cases, sliding of the timber roof off the masonry wall was observed. Since clay bricks are produced in large numbers and at a low cost without any standard, its quality is much dependent on the local conditions and circumstances. The most salient damage features of non-engineered buildings were:

1. Failures at corners of walls and at doors and window openings
2. Roof system sliding off the supporting walls
3. Shear, flexural or combined cracking of masonry brick walls
4. Failures at connection regions between roof, wall and foundations

A number of buildings in the area are non-ductile reinforced concrete structures with unreinforced masonry infill. The infill masonry consists primarily of solid bricks, although in some cases concrete blocks are used. The floor diaphragm consists of beams and slab construction supported by columns. Smooth bars are commonly used for the longitudinal reinforcement of beams and columns because of their lower cost compared to deformed bars. Roof structures are flat or pitched having, in many cases, a steel framing and tiled roofing. The anchorage of the infill wall to the roof system is poor or nonexistent.

Many of these buildings collapsed or were seriously damaged. Structural damage can be attributed to non-ductile detailing, insufficient confinement reinforcement in columns, lack of lateral resisting system, and poor quality construction. Short-column effect and soft-story actions contributed to the damage in some of the buildings. Nonstructural damage in the infill walls was observed in various low-rise buildings, especially at the lower floors. The BPKP (Badan Pengawasan Keuangan dan Pembangunan) governmental building collapsed due to poor detailing and insufficient confinement reinforcement (Fig.16).

NOTES FROM OBSERVATION

According to Fig.17, Yogyakarta region was classified in zone 3, which the ground design acceleration is 0.3g for rock (SB in UBC 1997) and 0.36g for soil (SD in UBC 1997). If a response modification factor R of 5 is assumed for low ductility structures, and an amplification factor of 2.5 is used, the seismic coefficient for design would be 0.15 to 0.18. As calculated by Elnashai et al. (2006), the spectra indicate that low ductility structures (μ=2) were subjected to lateral force coefficients in the region of 0.6 to 0.7, about 4 to 5 times as much as the code coefficient. Even for long period structures, the seismic code coefficient from the calculated spectra is about 0.15 or more, much higher than the code would have indicated. Consequently, even if these structures were designed to resist seismic forces according to the code, they would have suffered unexpectedly high levels of damage. Lesson can be learned from this situation that the Yogyakarta government must conduct micro-zone of ground amplification particularly in some areas which got severity level of damages. Although the Indonesian seismic code includes ductility detailing requirements, these were not satisfied in many of the damaged multistory RC buildings. Ductile detailing was rarely observed, and in some cases large buildings appeared to have been designed without the assistance of qualified engineers.

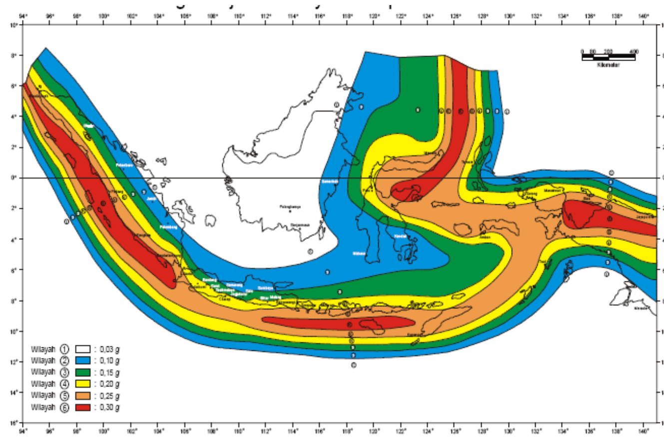


Fig.17. Indonesian ground design acceleration in rock formation

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